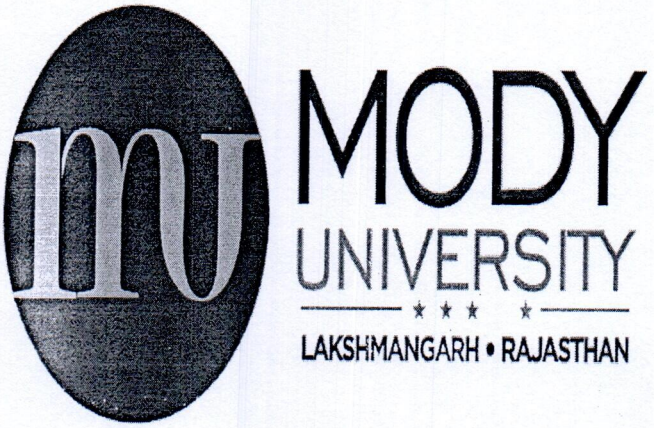
Sliding mode control
of
STATCOM
using
Cascaded multilevel power inverters



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1. INTRODUCTION:

Electronic power converters are non-linear, discrete and variable structure systems. Power converter control designer should deal with-

- Linearizing techniques (average circuit models, state space averaging techniques)
- Modulators (1-phase and 3-phase etc)
- Control methods (voltage mode and current mode control etc.)
- To control electronic power converters, a systematic approach able to deal with their variable structure and non-linearity should be used.
- Variable structure control (sliding mode) is the technique of choice as-
- Is appropriate to the on-off behavior of power switches. But the main drawback of this is chattering. The chattering is intrinsic to electronic power converters and cannot be completely eliminated.
- Is able to study the converter stability.
- Provides almost no overshoot and no steady state error.
- Uses Just In Time (JIT) switching action. When using turn off controlled power semiconductor.
- Adds robustness behavior concerning parameter variation and invariance.
- Provides insensitivity to non-linearity and disturbance.
- Can reduce the system order.
- Provides better tracking performances and faster dynamics than linear controllers.

Numerous industrial applications have begun to require higher power apparatus in recent years. Some medium voltage motor drives and utility applications require medium voltage and megawatt power. Therefore,

- A multilevel power conversion has been receiving increasing attention in the past few years for high power application.
- These converters are suitable in high voltage and high power applications due to their ability to synthesize waveforms with better harmonic spectrum and attain higher voltage with a limited maximum device rating.

2. Sliding mode in Variable structure system (VSS):

Variable structure control with sliding mode control was first proposed and elaborated in the early 1950's in the Soviet Union by Emelyanov and several co-researchers.

- Variable structure systems consist of a set of continuous subsystems with a proper switching logic and, as a result, control actions are discontinuous functions of system state, disturbances and reference input.

- Controller Structure around the plant is changed by some external influence to obtain desired plant response.
- High-speed Switching Control. For example, the gain in the feedback path switches between two values according to some rule.
- Switching occurs with respect to a switching surface in State Space.
- Individual Structures may be unstable, but the Variable Structure is asymptotically stable.
- The major reasons for variables structure control being of exceptional significance in recent control studies can be summarized as follows:
- The uses of variable structure theory is not limited to just controller design purposes. Its general principles are successfully applicable for other control problems such as linearization, finite time converging state observers and order reduction.
- In sliding mode, state trajectories are confined to a reduced order manifold. Therefore, the effective system order reduces and the original control problem can be decoupled into smaller order, independent sub-problem.
- A system is described by the following differential equation, represent the system in state space

$$\frac{d^3x}{dt^3}+3\frac{d^2x}{dt^2}+4\frac{dx}{dt}+4x=u_1(t)+3u_2(t)+4u_3(t)$$

and output are

$$y_1=4\frac{dx}{dt}+3u_1 \qquad y_2=\frac{d^2x}{dt^2}+4u_2+u_3$$

Answer: Select the state variables-

$$x_1=x$$

$$\dot{x_1}=\dot{x}=x_2$$

$$\dot{x_2}=x_3$$

$$\dot{x_3}=u_1(t)+3u_2(t)+4u_3(t)-3x_3-4x_2-4x_1$$

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ -4 & -4 & -3\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix}+\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 1 & 3 & 4\end{bmatrix}\begin{bmatrix}u_1\\ u_2\\ u_3\end{bmatrix}$$

Output:

$$y_1 = 4x_2 + 3u_1$$

$$y_2 = x_3 + 4u_2 + u_3$$

$$\begin{bmatrix}y_1\\ y_2\end{bmatrix}=\begin{bmatrix}0 & 4 & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix}+\begin{bmatrix}3 & 0 & 0\\ 0 & 4 & 1\end{bmatrix}\begin{bmatrix}u_1\\ u_2\\ u_3\end{bmatrix}$$

The sliding mode control approach is recognized as one of the efficient tools to design robust controllers for complex high-order nonlinear dynamic plant operating under uncertainty conditions. The research in this area was initiated in the former Soviet Union about 40 years ago. In control theory, sliding mode control, or SMC, is a non-linear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to "slide" along a cross-section of the system's normal behavior.

- Sliding mode control uses a relay in the feedback loop to drive a state-trajectory towards a 'sliding surface' and maintain it on this surface for all time. So that the sliding surface is designed while the state-trajectory is in contact, the system exhibits desired dynamic properties and is invariant to matched uncertainty.

- The state feedback control law is not a continuous function of time. Instead, it can switch from one continuous structure to another based on the current position in the state space.

- Hence, sliding mode control is a variable structure control method. The multiple control structures are designed so that trajectories always move toward an adjacent region with a different control structure, and so the ultimate trajectory will not exist entirely within one control structure. Instead, it will slide along the boundaries of the control structures. The motion of the system as it slides along these boundaries is called a sliding mode and the geometrical locus consisting of the boundaries is called the sliding surface.

- Sliding mode control will be important for control design that the sliding mode equation

  a) is of reduced order

  b) does not depend of control

  c) depends on the equation of switching surface.

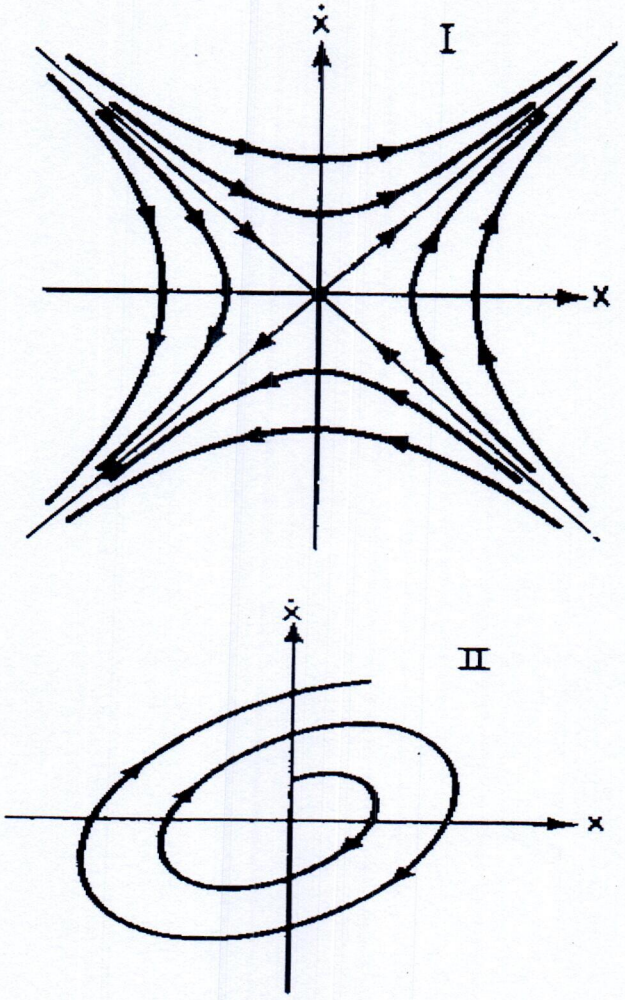

Figure 1. State plane of two unstable structures

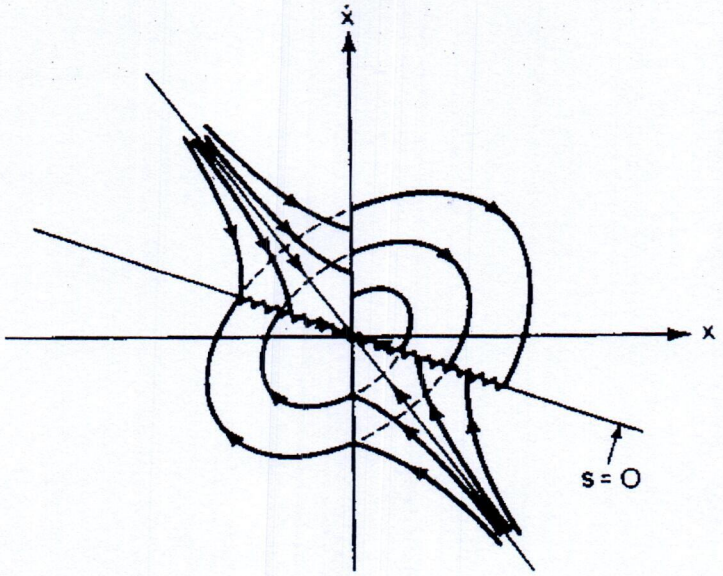

Figure 2. State plane of variable structure system

3. POWER CONVERTERS:

A power converter is an electrical or electro-mechanical device for converting electrical energy. It may be converting AC to or from DC, or the voltage, or frequency, or some combination of these. Amongst the many devices that are used for this purpose are-

a) Switched-mode power supply (AC to DC)

b) Rectifier (AC to DC)

c) Inverter (DC to AC)

d) Motor generator set

e) Chopper (DC-DC converter)

f) Transformer / autotransformer

4. Sliding mode control of DSTATCOM:

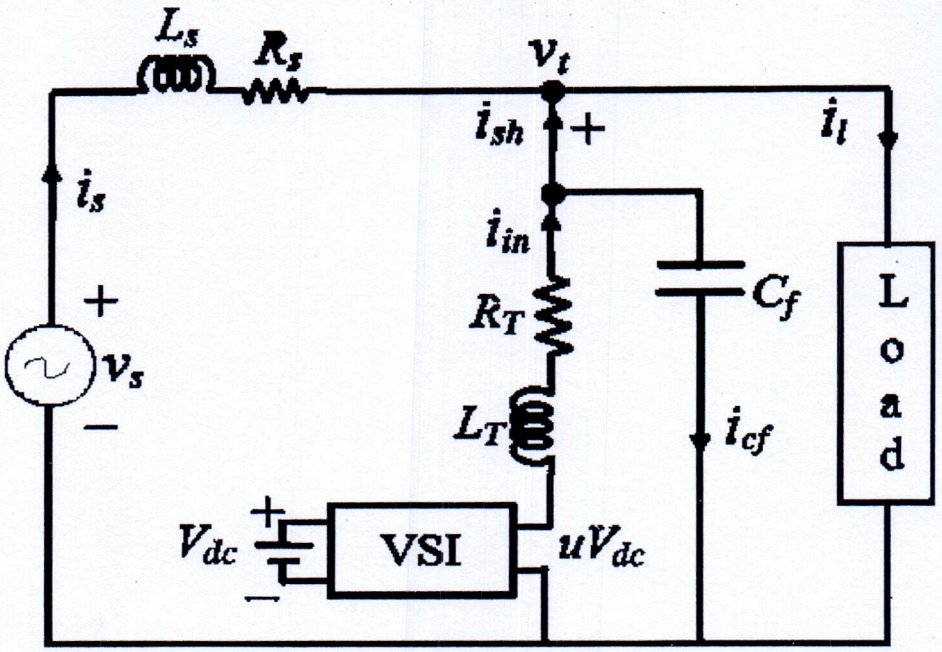

Figure 3. Load voltage control using DSTATCOM

Switching logic has discrete values between -1 and +1, depending upon the number of levels of the VSI.

Example: For a 5-level inverter-

Discrete values are: -1 -1/2 0 ½ 1

& for 7-level inverter-

Discrete values are: -1 -1/2 -3/2 0 3/2 ½ 1 and so on.

In order to design a control law independent of the load and source parameters,

State vector is- $z_T = [\dot{v}_t v_t]$

State variable v_t is the terminal voltage or point of common coupling (PCC) voltage $\dot{v}_t$ is derivative of v_t

And, the state-space representation of the system is

$$\dot{z} = Fz + g_1 u + g_2 d$$

$$v_t = h_o z$$

Where,

$$F = \begin{bmatrix} \frac{-R_T}{L_T} & \frac{-1}{C_f L_T} \\ 1 & 0 \end{bmatrix} g_1 = \begin{bmatrix} \frac{V_{dc}}{C_f L_T} \\ 0 \end{bmatrix} g_2 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$h_o = [0 \quad 1]$$

Variable 'd' is considered to be a periodic source that depends upon the shunt current &

$$d = -\frac{1}{C_f}\left(\frac{di_{sh}}{dt}\right) - \left(\frac{R_T}{C_f L_T}\right) i_{sh}$$

5. Literature Survey:

S.No.	Author & Year	Title	Overview
1.	**Vadim Utkin,** IEEE transaction ON AUTOMATIC control vol AC 22 no. 2 april 1977	Survey paper: Variable structure systems with sliding modes	Variable structure systems consist of a set of continuous subsystems together with suitable switching logic. Advantageous properties result from changing structures according to this switching logic. Design and analysis for this class of systems are surveyed in this paper.
2.	**John Y. Hung, Member, IEEE, Weibing Gao, SeniorMember, IEEE, and James C.**	Variable Structure Control: A Survey	Tutorial account of variable structure control with sliding mode is presented in this paper. The purpose is to introduce in a concise manner the fundamental theory, main results, and practical applications of this powerful control system design approach. This approach

	Hung, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 40, NO. 1, FEBRUARY 1993		is particularly attractive for the control of nonlinear systems. Prominent characteristics such as invariance, robustness, order reduction, and control chattering are discussed in detail. Methods for coping with chattering are presented. Both linear and nonlinear systems are considered. Future research areas are suggested and an extensive list of references is included.
3.	**Charles P. Coleman and Datta Godbole**	A Comparison of Robustness: Fuzzy Logic, PID and Sliding mode control	This work is performed in order to foster and promote unbiased and accurate comparison of fuzzy logic control and classical control design methodologies. Robust fuzzy logic, PID and sliding mode controllers are designed to control the speed of a nominal third order linear time-invariant model of a motor. The step response performance of each controllers applied to the nominal and two perturbed motor plants, is presented.
4.	**Asif Sabanovic, Karel Jezernik and Nadira Sabanovic**	Sliding mode applications in power electronics and electrical drives	Control system design of switching power converters and electrical machines based on the sliding mode approach is presented. The structure similarities among switching converters and electrical machines are used to show that the same structure of the controller could be used for plants under consideration.
5.	**G. Spiazzi and P. Mattavelli,Rossetto, L. Malesani**	Application of sliding mode control to switch power supplies	Switch-mode power supplies represent a particular class of variable structure systems (VSS). Thus, they can take advantage of non-linear control techniques developed for this class of systems. Sliding mode control extends the properties of hysteresis control to multi-variable environments, resulting in stability even for large supply and load variations, good dynamics response and simple implementation. Application to dc-dc converters, as well as rectifiers and inverters is analyzed and provisions to overcome the inherent drawbacks of sliding mode

			control, i.e. variable switching frequency and possible steady-state errors, are described.
6.	**Siew-chong Tan, Y.M. Lai and Chi K. Tse**	Indirect sliding mode control of power converters via double integral sliding surface	The steady state regulation error in power converters that use the conventional hysteresis-modulation based sliding mode controller can be suppressed through the incorporation of an additional integral term of the state variables into the controller. This paper presents an in-depth study of the phenomenon and offers a solution to the problem.
7.	**Bindeshwar Singh, Nupur Mittal, Dr. K.S. Verma, Dr. Dependra Singh, S.P. Singh, Rahul Dixit, Manvendra Singh and Aanchal Baranwal**	Multilevel inverter: A literature survey on topologies and control stategies	Multilevel inverters have been attracting in favor of academia as well as industry in the recent decade for high power and medium voltage energy control. In addition, they can synthesize switched waveforms with lower levels of harmonic distortion than an equivalently rated two-level converter. The multilevel concept is used to decrease the harmonic distortion in the output waveform without decreasing the inverter power output.
8.	**M.R. Vishnupriya, Mr. J. Gowri Shankar and Mr. M. Balasubramani**	Implementation of multilevel inverter using MPPT based sliding mode control for PV cell	Photovoltaic array is used as source. The output for solar module is connected to the battery. So, the supply is given continuously by the battery to the system. The output of the solar may vary due to the radiation and will affect the battery. So, the life time of battery is reduced. It is necessary to protect the battery from the non-linear solar energy, charge controller is used. In order to track maximum power, sliding mode controller is used.
9.	**J. Fernando, A Silva**	Sliding mode control of multilevel power converters	The application of sliding mode, a non-linear robust and self-contained approach to the conterol problem of electronic power converters is outlined and illustrated. On-line sliding mode control is suited to multilevel

			power converters as they are inherently variable structure systems. Obtained controllers are robust concerning parameter variation and perturbations and provide "Just In Time" switching.
10.	**Vuyyuru Swapna, Aswani Kumar Eedara, International Journal of modern engineering research (IJMER) vol.2, issue 6, Nov-Dec. 2012**	Sliding mode control of DSTATCOM using Seven level multilevel inverter	In Distribution system (DS), the majority of power consumption has been drawn in reactive loads. These loads are drawn in low power factor and therefore give rise to reactive power burden in the distribution system. So that DSTATCOM controller is used to compensate reactive power, correction of power factor and elimination of current harmonics. This paper presence the 7-level cascaded H-bridge inverter as DSTATCOM for compensation of balanced and unbalanced linear and non-linear loads by using level shifted and phase shifted PWM techniques. The advantage of CHB inverter is reducing the number of switches and thus switching losses.

6. CASCADED MULTILEVEL INVERTER BASED ON STATCOM:

We considered a multilevel inverter. So, first of all define the single inverter and then also explain the multilevel inverter. A device that converts dc power into ac power at desired output voltage and frequency is called an inverter. Some industrial applications of inverters are for adjustable-speed ac drives, induction heating, stand by air-craft power supplies, UPS (uninterruptible power supplies) for computers, HVDC transmission lines etc.

Cascaded multilevel inverter:

- The Cascaded Multilevel Inverters are used in Flexible AC Transmission System (FACTS) applications.
- Harmonic distortions are minimized by using STATCOM based Cascaded Multilevel Inverters.

- A STATCOM based cascaded multilevel inverter is used to implement the reactive power control using abc coordinates.
- A cascade multilevel inverter is a power electronic device built to synthesize a desired AC voltage from several levels of DC voltages.
- Multilevel inverter has become attractive in the power industries and it can be applied in many application especially on improvement of the power quality.
- As the number of levels increases, the synthesized output waveform has more steps, which produces a staircase wave that approaches a desired waveform. Also, as more steps are added to the waveform, the harmonic distortion of the output wave decreases, approaching zero as the number of levels increases. As the number of levels increases, the voltage that can be spanned by summing multiple voltage levels also increases.

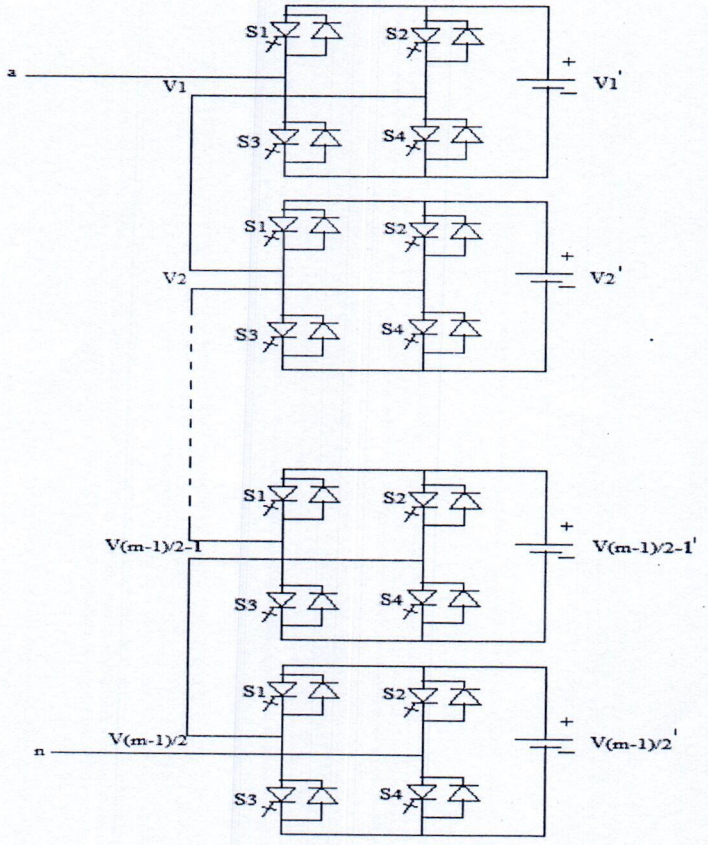

Figure 4. Schematic of a 1-phase cascaded-multilevel converter

In this circuit, a single-phase structure of an m-level cascaded inverter with SDCSs. The ac terminal voltages of different level inverters are connected in series. Each inverter level can generate three different voltage outputs, +Vdc, 0, and –Vdc by connecting the dc source to the ac output by different combinations of the four switches, S1, S2, S3, and S4. To obtain +Vdc, switches S1 and S4 are turned on, whereas –Vdc can be obtained by turning on switches S2 and S3. By turning on S1 and S2 or S3 and S4, the output voltage is 0. The ac outputs of each of the different full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs. The number of output phase voltage levels 'm' in a cascade inverter is defined by m=2s+1, where s is the number of separate dc sources. Each single-phase full bridge inverter can generate three level outputs, +Vdc, 0, and –Vdc.

(a) 3-phase cascaded 11-level inverter:

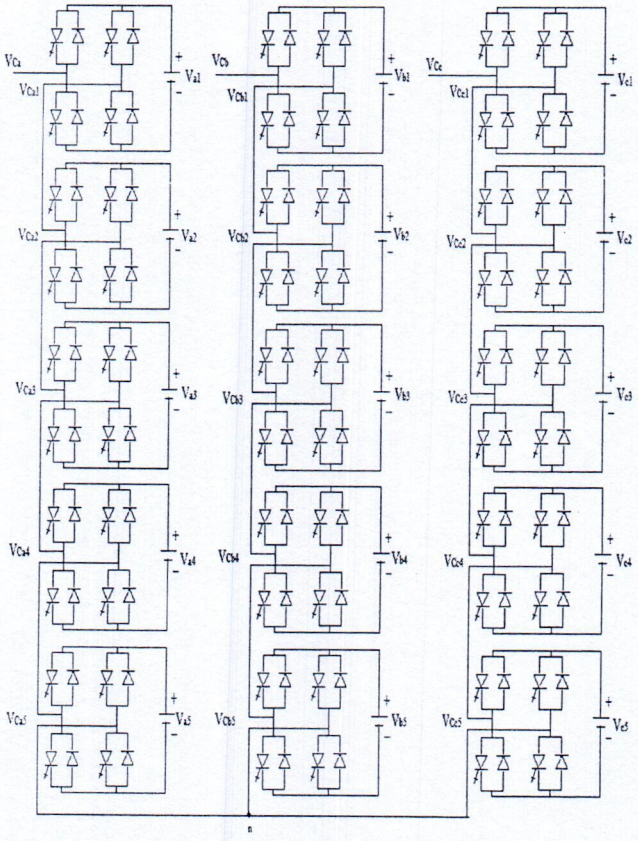

Figure 5. Three phase 11-level CHB Multilevel converter

The cascaded 11-level inverter requires five separate dc sources per phase leg; this means that five H-bridge inverters are used for single phase structure.

One of the terminal of each single phase 11-levels cascaded H-bridge multilevel is connected as star, while the other terminal of each single phase cascaded H-bridge multilevel inverter is connected to a 3-phase series load.

A 3-phase structure of an 11-level cascaded inverter with 5 SDCs is illustrated in figure.

This type of cascaded H-bridge multilevel inverter has been designed and simulated using MATLAB SimpowerSystems. The multilevel circuit is illustrated in figure.

The phase output voltage is synthesized by the sum of individual inverter output i.e.

Van = V1+V2+V3+.....+Vn----------(1)

Therefore, the phase voltage for 11-level cascaded inverter is,

Van = V1+V2+V3+V4+V5----------(2)

For a stepped waveform such as the one depicted in figure (6) with s steps, the Fourier Transform for this waveform-

$$V(\text{wt}) = \frac{4V_{dc}}{\pi} \sum_{n} [\cos(n\theta_1) + \cos(n\theta_2) + \cdots + \cos(n\theta_s)] \frac{\sin(\text{nwt})}{\text{n}}$$

----------(3)

From above equation, the magnitudes of the Fourier coefficients when normalized with respect to Vdc are as follows:

$$H(n) = \frac{4}{\pi n} \sum_{n=1}^{\infty} [\cos(n\theta_1) + \cos(n\theta_2) + \cdots + \cos(n\theta_s)]$$

----------(4)

Where n = 1, 3, 5, 7…

The conducting angles θ1, θ2,.....θs can be chosen such that the voltage total harmonic distortion is a minimum.

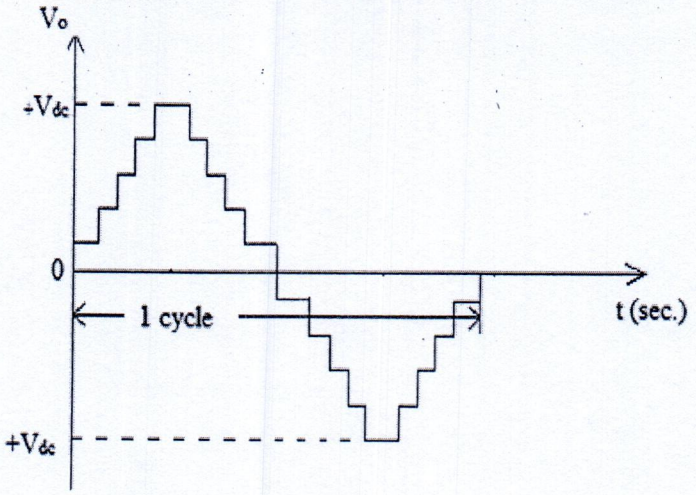

Figure 6. Steeped waveform for 1-phase 11-level inverter

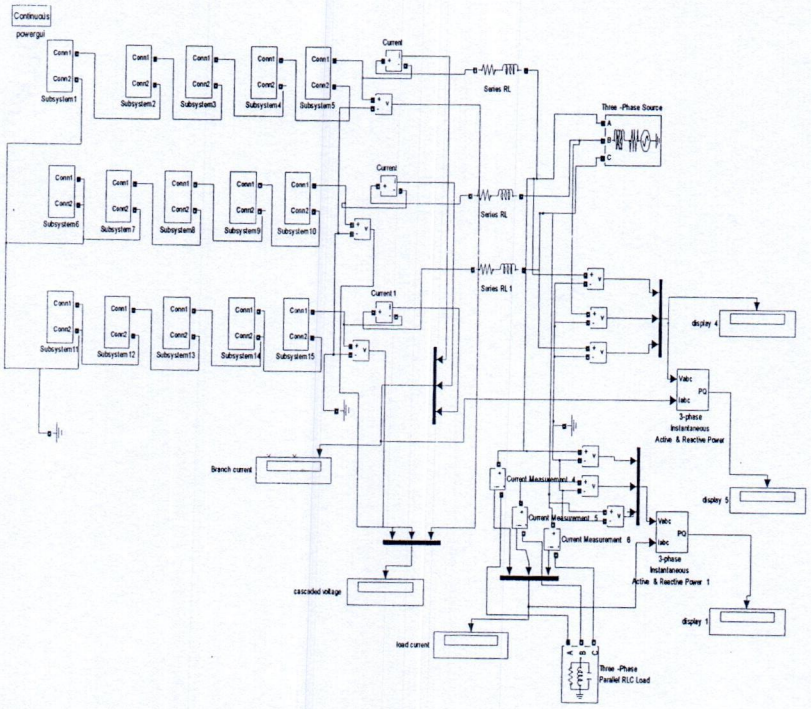

Figure 7. Simulation model of 3-phase Cascaded 11- level converter

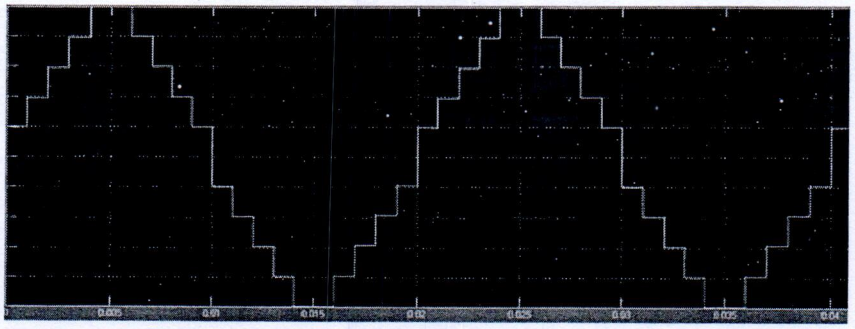

Figure 8. Single-phase cascaded 11-level inverter waveform

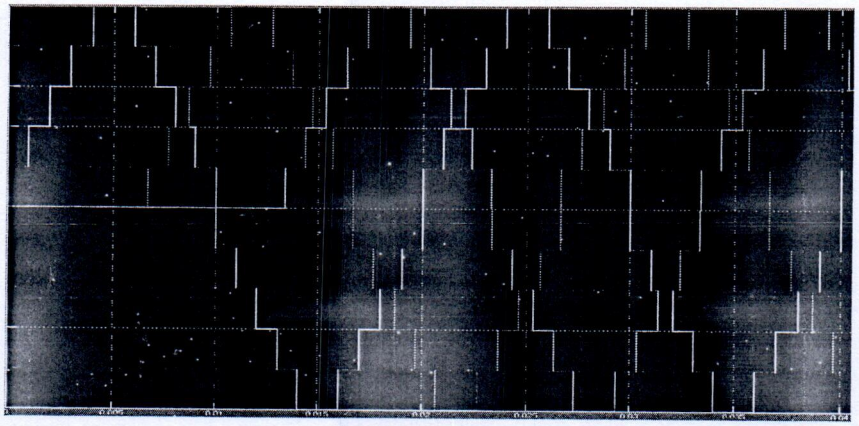

Figure 9. Three-phase cascaded 11-level inverter waveform

(b) 3-phase cascaded 13-level inverter:

In 13-level, the number of SDCSs is 5. To compare the values in terms of output voltage with the three phase 11-levels cascaded H-bridge multilevel inverter and 13- level inverters as shown in figure.

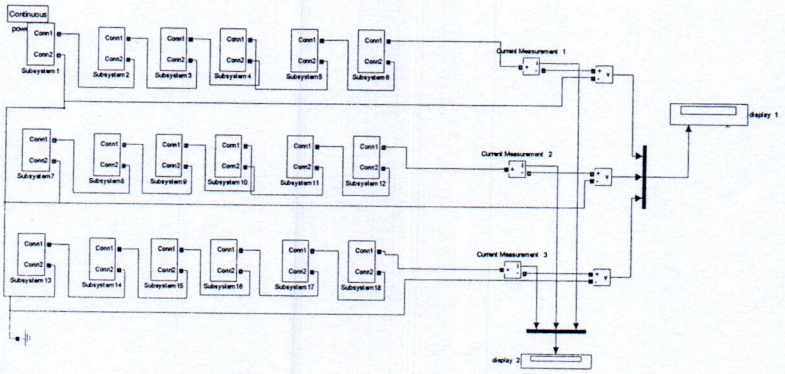

Figure 10. Simulation model of 3-phase Cascaded 13- level converter

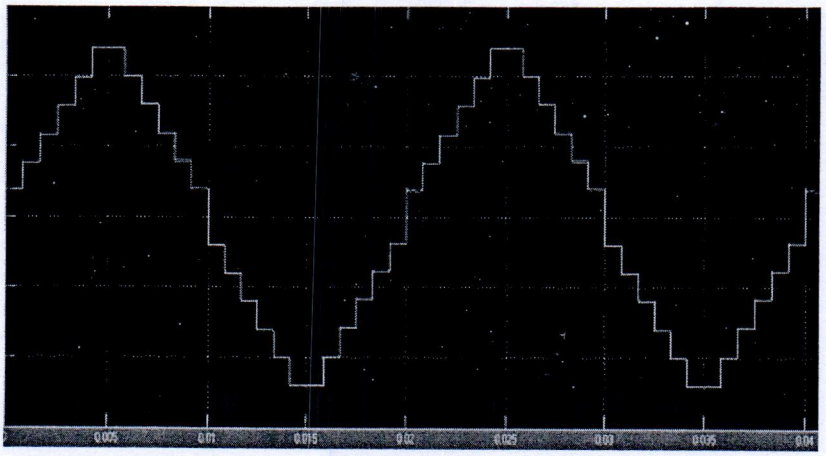

Figure 11. Single-phase cascaded 13-level inverter waveform

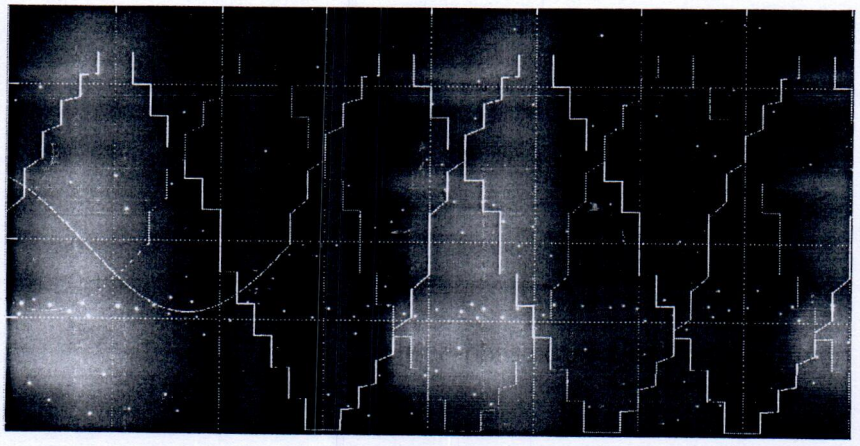

Figure 12. Three-phase cascaded 11-level inverter waveform

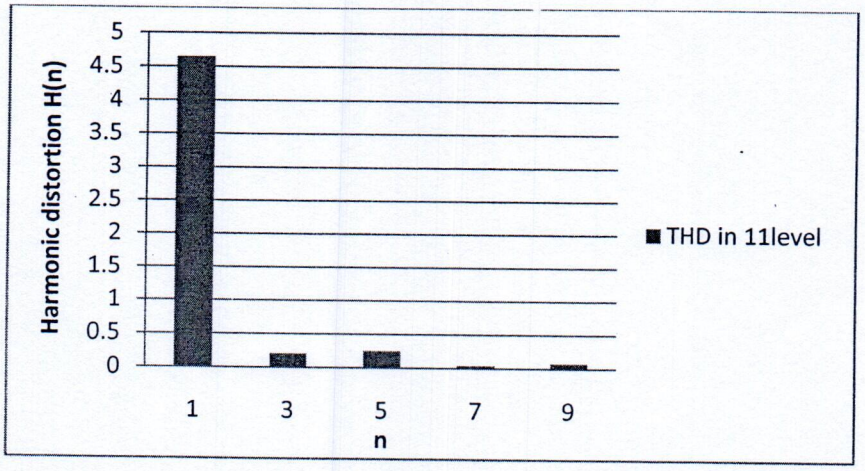

Figure 13. Harmonic distortions in STATCOM based cascaded eleven level inverter v/s nth orders

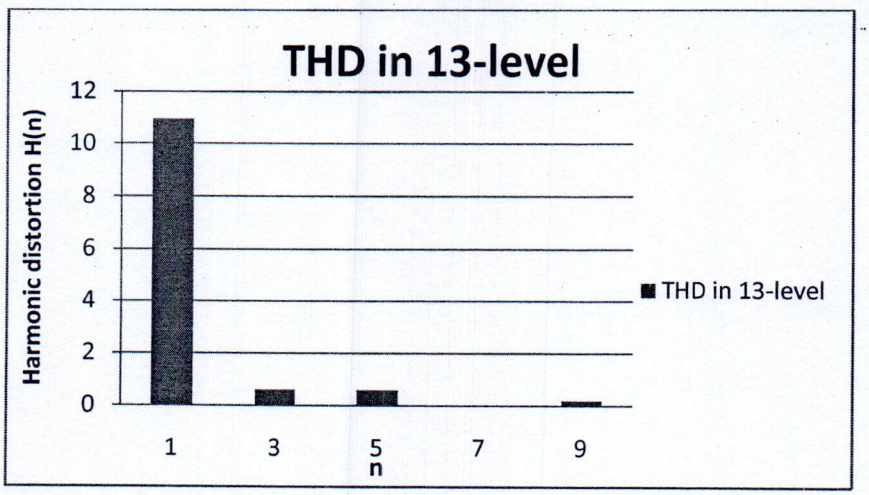

Figure 14. Harmonic distortions in STATCOM based cascaded eleven level inverter v/s nth orders

(c) STATCOM (STATIC SYNCHRONOUS COMPENSATOR):

- The STATCOM is the first power-converter-based shunt-connected controller. Instead of directly deriving reactive power from the energy-storage components, the STATCOM basically circulates power with the connected network.
- A representative of converter based VAR compensators is STATCOM, Static synchronous compensator. STATCOM is a self-commutated AC/DC power converter connected in parallel with the power system through coupling reactors.
- A STATCOM is a voltage source converter (VSC)-based device, with the voltage source behind a reactor. However, its active power capability can be increased if a suitable energy storage device is connected across the DC capacitor. The reactive power at the terminals of the STATCOM depends on the amplitude of the voltage source.
- For example, if the terminal voltage of the VSC is higher than the AC voltage at the point of connection, the STATCOM generates reactive current; on the other hand, when the amplitude of the voltage source is lower than the AC voltage, it absorbs reactive power. The response time of a STATCOM is shorter than that of an SVC, mainly due to the fast switching times provided by the IGBTs of the voltage source converter. The STATCOM

also provides better reactive power support at low AC voltages than an SVC, since the reactive power from a STATCOM decreases linearly with the AC voltage.

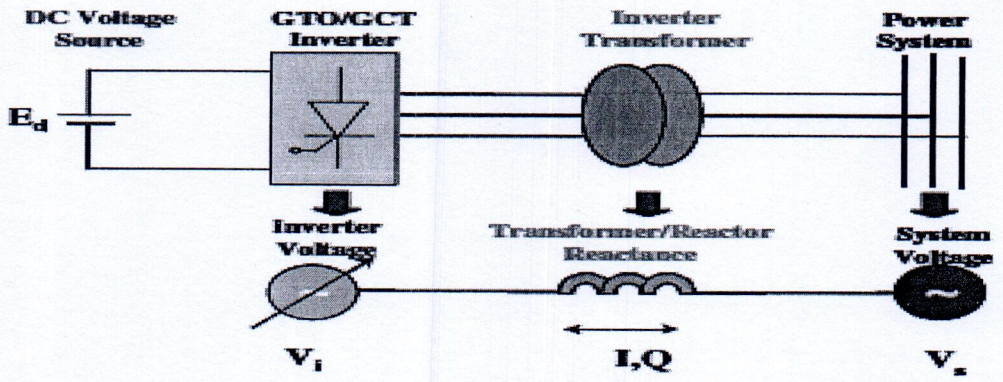

Figure 15. Static Synchronous Compensator (STATCOM)

(d) Power circuit and operation principle-

An eleven level, three-phase STATCOM based on the cascading configuration is illustrated in figure.

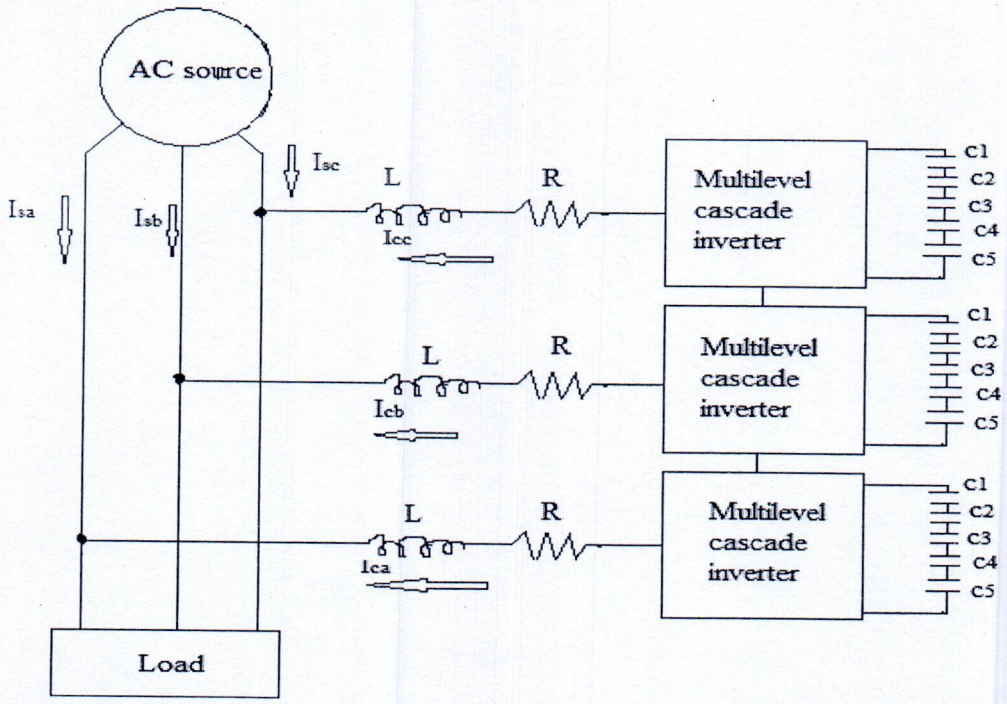

Figure 16. Structure of the STATCOM with cascade multilevel inverter

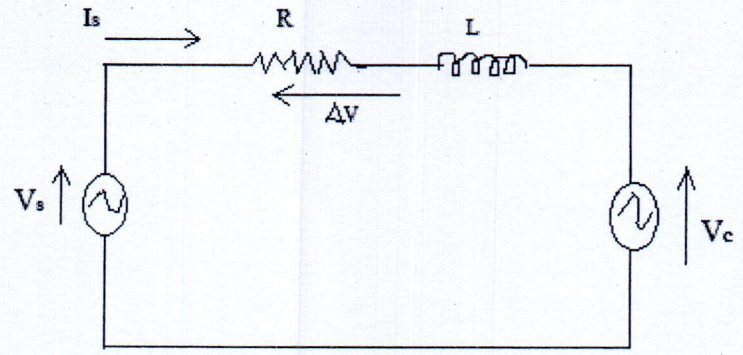

Figure 17. Single phase equivalent circuit

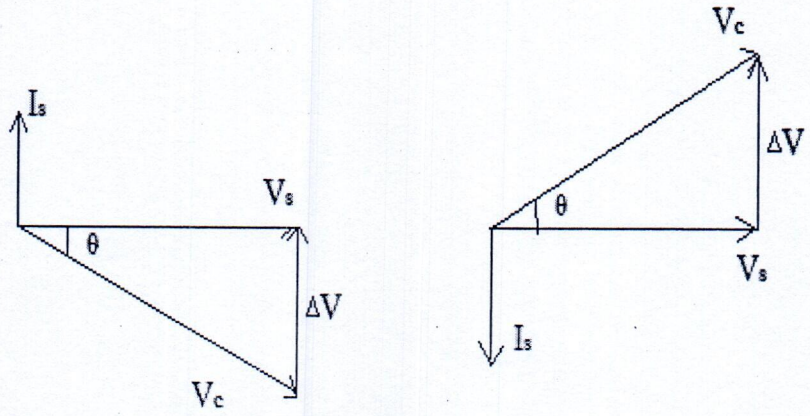

Figure 18. Phasor diagram of the STATCOM

(e) Control of reactive power:

- It is well known that the amount and type of reactive power exchange between the STATCOM and the system can be adjusted by controlling the magnitude of STATCOM output voltage with respect to that of system voltage.
- Reactive power,

Q = V(statcom)-V(system)

When Q is positive, the STATCOM supplies reactive power to the system. Otherwise, the STATCOM absorbs reactive power from the system.

- In my work, I have considered the phase angle difference between STATCOM voltage and system voltage to be zero by adjusting the branch impedance.

Real power exchange between STATCOM and system is-

$P = \{V(system)*V(statcom)\}*Sin\alpha\}/ X$

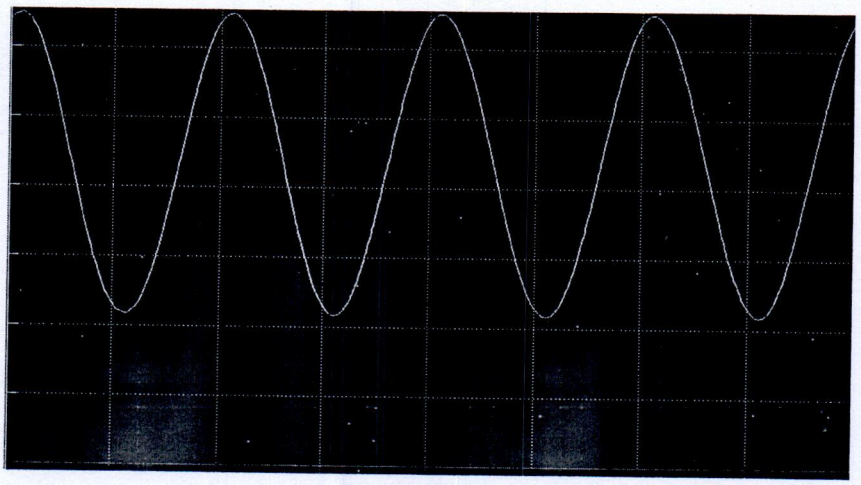

Figure 19. Reactive power in 3-phase cascaded 11-level inverter based STATCOM

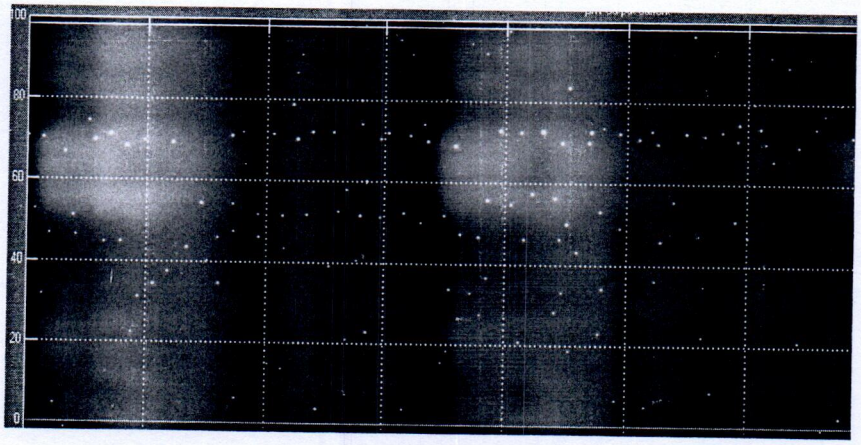

Figure 20. Active and Reactive power in 3-phase cascaded 13-level inverter based STATCOM

7. CONCLUSION:

In conclusion, among the mature multilevel inverter topologies, the cascaded-multilevel VSC is the most promising alternative for the STATCOM application. It requires the least number of components to achieve the same number of output voltage levels. With its modularized structure, the Cascaded Multilevel Inverter can flexibly expand the output power capability and is favorable to manufacturing. Control complexity of the Cascaded Multilevel Inverter is, however, directly proportional to the number of H-bridge inverters. In the STATCOM application, the AC

voltage of each H-bridge converter is derived from its DC capacitor voltage or supply voltage, which needs to be individually regulated. As the number of voltage levels increases, the voltage-imbalance problem becomes more of a concern.

8. RESEARCH PLAN:

In research work, An Eleven and thirteen level inverter based STATCOM is proposed for the application to the three phase medium voltage distribution system and the results are shown through the MATLAB/SimPowerSystem and after that I will be applying the sliding mode controller. Sliding mode control (SMC) can be used as a controller in STATCOM based cascaded multilevel inverter for removing the chattering in the system. This system can also be used in spacecraft tracking system.

An extension of the use of the boundary control method using second order switching functions for controlling three phase multilevel inverters.

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